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A Study on Interpretation of Medieval Vocal Repertoire through Auralisation: An Acoustic Reconstruction of the Great Chapel of the Palais des Papes

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A Study on Interpretation of Medieval Vocal Repertoire through

Auralisation: An Acoustic Reconstruction of the Great Chapel of the Palais des Papes

This research undertakes an interdisciplinary investigation that combines medieval musicology and virtual acoustics applied to heritage spaces. It is centred around acoustic reconstructions of the Great Chapel within the Palais des Papes in Avignon during various historical periods. This chapel served as a significant venue for choir singing of the *Ars Nova* musical repertoire in the 14th century, coinciding with the Palais des Papes' role as the official residence of the papacy. The study presents a concise overview of the architectural history of the Palais des Papes and its chapels, followed by the methodology for virtually reconstructing the acoustics of the Great Chapel under diverse conditions. An experimental phase employed a choir ensemble specialising in the *Ars Nova* repertoire, immersing singers in the virtual acoustics of the Great Chapel using a real-time room auralisation system designed for headphone reproduction. Through this experiment, we examined the singers' musical performance in response to the simulated acoustics. The efficacy of the proposed auralisation system was assessed based on participants' feedback regarding its ability to accurately replicate the acoustic conditions of an authentic music performance space.

Keywords: virtual acoustics reconstruction, room auralisation, heritage space, polyphonic singing

Introduction

The establishment of the papacy in Avignon in the 14th century allowed the city to become the centre of the Christian world, as well as a fertile ground for musical art: an art serving the papal politics, the Church, and the entire city as a whole. In a diverse medieval culture where transmission of knowledge primarily occurred orally, the sounds of both music and of speech were crucial elements in the exercise of papal power, as well as in the daily activities of the city's inhabitants.

Our Lord took his meal in a hall accompanied by sixteen cardinals and twenty other individuals chosen from among prelates and other secular lords. There was also a table with twelve choirboys, the eldest of whom was twelve years old, all nephews or close relatives of the pope, who for some time now, come and go where he goes and have masters, knights, and squires who raise, educate, and serve them. [...] He was carried by squires and made his entrance accompanied by knights, while various musical instruments were played. I believe that the sound of the instruments, combined with the joyful cries of the onlookers, could be heard all the way to Avignon. [...] The ninth course arrived, and as an interlude, the singing of an unseen choir was heard: voices of all kinds, deep, less deep, medium, high, childlike, of exquisite sweetness, which brought silence throughout the hall because everyone's attentive ears silenced their tongues, so sweet was the sweet melody.¹

This excerpt from the Chronicle of Gentilly (De Loye 1988) is a valuable testimony that evokes a musical activity in the presence of the Sovereign Pontiff in Avignon. The scene takes place around 1342, during a time when the Palais des Papes was the official residence of the papacy, in the presence of Pope Clement VI, one of the most significant popes for the development of the arts and the architectural evolution of the Palais des Papes. He was the pope of expansion, which allowed the papal palace to achieve unparalleled functionality,

¹ Our translation of the original Florentine Italian, translated to French by Georges De Loye. “Notre seigneur prit son repas dans une salle en compagnie de seize cardinaux et de vingt autres personnes choisies parmi des prélats et autres seigneurs laïques. Il y avait aussi une table où étaient douze enfants de chœur dont l’aîné avait douze ans, tous neveux ou parents proches du pape et qui, depuis quelque temps, vont et viennent là où il se rend et ont des maîtres, des chevaliers et des écuyers qui les élèvent, les éduquent et les servent. [...] Il fut porté par des écuyers et fit son entrée accompagnée par les chevaliers avec des instruments de musique de différentes sortes. Je crois que le son des instruments, ajouté aux cris de joie des assistants, se firent entendre jusqu’à Avignon. [...] Le neuvième service arriva et, comme intermède, on entendit le chant d’un chœur de chantres sans les voir: des voix de toute sortes graves, moins graves, moyennes, hautes, enfantines, d’une douceur exquise qui amenèrent le silence dans toute la salle parce que les oreilles attentives de tout le monde firent taire les langues tant était suave la douce mélodie.”

symbolised by the construction of new buildings to the south, known as the *opus novum*, and particularly the construction of the Clementine Chapel, also known as the Great Chapel (Figure 1, item 10, 1st floor). Furthermore, certain political musical productions created during his pontificate seem closely linked to the architecture of the premises, such as the motet *Petre Clemens / Luggentium siccentur / Non est inventus* and its structural connection to the arrangement of the Great Chapel in successive bays (Ferrando 2014a). The Great Audience Hall (Figure 1, item 10, ground floor), where the Rota Tribunal was located, and the Window of Indulgence (Figure 1, item 8) overlooking the enclosed courtyard, now the *Cour d'Honneur* (Figure 1, item 7), are other examples of locations within the Palais des Papes whose architecture facilitates the dissemination of speech, liturgy, and musical art. This significant relationship between sound and architecture is materialised by the constant evolution during the 14th century of the places for musical creation within the Palais des Papes, both aesthetically and technically.

1. Notre-Dame des Doms cathedral
2. Chapel of Saint-Étienne, a.k.a. Chapel of Benedict XII
3. Kitchen Tower
4. Cloister courtyard
5. Ground floor: Consistory Hall; 1st floor: Grand Tinel
6. Saint-John Tower. Ground floor: chapel of Saint-John; 1st floor: chapel of Saint-Martial
7. *Cour d'Honneur*
8. Window of Indulgence
9. Wardrobe Tower. 1st floor: chapel of Saint-Michael
10. Ground floor: Great Audience Hall; 1st floor: **Great Chapel**
11. Peyrolierie rock
12. Main façade

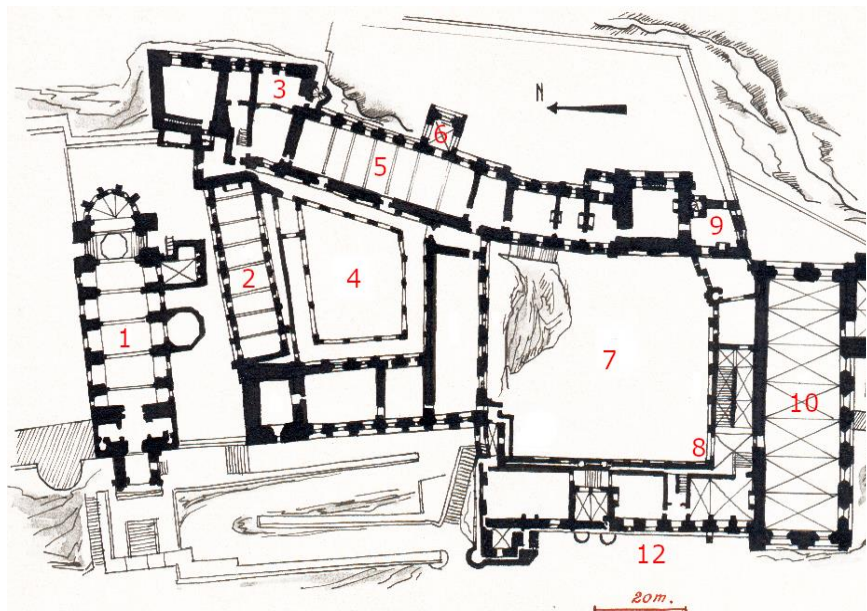


Figure 1. Floorplan of the Palais des Papes in Avignon. Source: adapted from original drawing by Viollet-le-Duc (1858, vol. 7, 32).

Motivation

In the last two decades, several series of medieval vocal music concerts were organised in the Great Chapel of the Palais des Papes, as the acoustics of that modern place are considered adequate for vocal music performance. The Great Chapel was renowned in the 14th century as one of the prominent venues for the practice of *Ars Nova*². However, its acoustics have likely evolved since the time when the papal chapel cantors performed there. Even though its modern-day architecture is largely similar to its medieval counterpart due to a renovation in the early 20th century aimed at restoring the Palais des Papes to its medieval condition, the Great Chapel has lost, along with its original function, its lavish decoration and period furniture. This historical evolution motivated our recreation of the historical acoustic conditions of a vocal performance in the Great Chapel. Thanks to progress offered by room acoustics modelling and auralisation techniques³, it was possible to study the musical interpretations of a vocal ensemble specialising in medieval music within the virtually reconstructed acoustics of the Great Chapel of the Palais des Papes.

This archaeoacoustic research, bringing together musicologists and acousticians in the context of the IMAPI⁴ (Musical Interpretation in Immersive Heritage Acoustics) and PHE⁵

² *Ars Nova* is a musical style that developed in France in the 14th century as the successor of the *Ars Antiqua* exemplified by the School of Notre-Dame. It allowed for a higher degree of musical expressiveness in the polyphony and for more elaborate rhythmic modes thanks to a new standardised system of musical notation, even though some studies have shown that interpreting *Ars Antiqua* and *Ars Nova* as two radically opposite styles is probably excessive (Tanay 1992).

³ Auralisation is the audio equivalent of visualisation, rendering the room acoustic measurement or simulation data audible. For a more detailed description, see Kleiner et al. (1993).

⁴ <https://imapi.hypotheses.org/>

⁵ <http://phe.pasthasears.eu/>

(the Past Has Ears) projects, was born out of the desire to investigate the interrelationships between historical production venues and heritage musical productions (Ferrando 2020; Ferrando 2022; Katz *et al.* 2020). The main objective centres around experimental research on the interpretation of heritage music in the virtually reconstructed acoustics of the Great Chapel of the Palais des Papes in different historical states (1362, 2022). For this purpose, professional singers specialising in medieval vocal repertoire participated in a laboratory experiment where they performed a corpus of 14th century music pieces, with the aim of studying historically informed musical practices and the resulting musical gestures (Ferrando and De Muynke 2022).

The Palais des Papes in Avignon and its chapels

In 1309, the Holy See relocated to Avignon, France and remained there until 1403 (Poisson 2004). While Clement V, the first pope of Avignon, initially established his residence in the former episcopal palace, Benedict XII, the second in the line of succession, began the first expansion phase (the Old Palace) in 1335. This was followed by a second expansion phase starting in 1342 under Pope Clement VI (the New Palace), which included the Great Chapel. The construction of the Palais des Papes was ultimately finished in 1367 when Pope Urbain V returned to Rome (Vingtain 1998, p.415). Thus emerged the Palais des Papes as it is recognized today, which holds the distinction of being the largest Gothic structure ever constructed. The evolution of its intrinsic structure during the 14th century entailed the creation or destruction of places where liturgical music was present. In particular, the number of chapels, where music accompanied various services (Matins, Lauds, Vespers, etc.), continued to evolve throughout the 14th century.

The first pontifical chapel resulted from the conversion in 1317 of the former parish church Saint-Étienne (Figure 1, item 2) from the episcopal palace under Jean XXII (Vingtain 1998, pp.74-75).

The Old Palace

The construction of the Old Palace, initiated by Benedict XII from 1335 onwards, included the extension of the papal chapel Saint-Étienne (Vingtain 1998, pp.98-99). Whereas it originally spanned two levels, the lower level was quickly converted, known to have served as a warehouse from 1338 (Labande 1925, p.52). The upper level remained the main liturgical building until the reign of his successor Clement VI. The Old Palace also included two new small chapels housed in the Saint-John tower (Figure 1, item 6), connecting to the Grand Tinel and the Consistory Hall (Figure 1, item 5): the lower-level chapel of Saint-John and the upper-level chapel of Saint-Martial.

During this period, an increased prominence of cantors accompanied the expansion of chapels within the building (Tomasello 1982, p.141 Ferrando 2007, p.87). This dual development reflects Benedict XII's aim to establish liturgical unity, influenced by Roman ceremonial practices and its musical traditions rooted in the *schola cantorum*. Subsequently, a novel institution, the *capella intrinseca*, gradually supplanted the legacy of Roman ceremonial practices (Tomasello 1982, pp.136-138). With this shift, cantors specialising in polyphonic singing assumed a more significant and professionalised role. These singers, recruited by the pope from Europe's finest, particularly from Northern France and Flanders, formed a professional choir of cantors. They held prestigious titles, received substantial salaries, garnered high esteem, and achieved great renown in the Christian world. Concurrently, the decision was made for the pontiff to appoint a *magister capelle*, i.e., a

chapel master, responsible for the chapel's liturgical, musical, and logistical aspects. The case of chapel master Pierre Sintier (Anheim 2008, p.123) serves as a compelling testament to this gradual transformation.

The New Palace

Clement VI presided over the expansion of the palace, a period marked by Roman impatience and demands for the pontiff's return to the seat of Saint-Peter in Rome. Despite this pressure, Clement VI, succeeding Benedict XII from 1342 onwards, expressed through the palace expansion his desire to establish a permanent residence in the Provençal city. He deemed the papal palace left by his predecessor inadequate in available space compared to the necessitated grandeur of the papal court, as well as insufficient in representing and perpetuating the actions of Saint-Peter on Earth. Consequently, he commissioned the construction of the New Palace, or *opus novum*, as an extension to the Old Palace.

The undertaking of the New Palace construction was immense and technologically complex, as illustrated by the excavation of the Peyrolierie rock in the south (see Figure 1, item 11). The new extensions featured the Kitchen Tower (see Figure 1, item 3), the Wardrobe Tower (see Figure 1, item 9) including the Chapel of Saint-Michael (Tomasello 1982, p.47), as well as a new aisle on two floors on the south side. This new aisle included the Great Audience Hall on the ground floor and the new papal chapel on the first floor: the Great Chapel (see Figure 1, item 10). Both the Great Audience Hall and the Great Chapel were adorned with ribbed vault ceilings, a technological innovation contrasting with the pointed barrel vault ceiling of the Chapel of Benedict XII. The Italian painter Matteo Giovannetti was requested by Clement VI to decorate the Great Audience Hall (see Figure 1, item 10), the chapel of Saint-John (see Figure 1, item 6, ground floor) and the chapel of

Saint-Martial (see Figure 1, item 6, 1st floor) with resplendent frescoes. The *opus novum* also included the construction of another aisle on the west side connecting the Old Palace in the north to the New Palace in the south, thereby enclosing a new open-air space, the *Cour d'Honneur* (see Figure 1, item 7). The main façade of the palace was transferred to this new aisle (see Figure 1, item 12).

Initially named *capella nova* and later known as *capella clementina*, the Great Chapel, with initial construction started in 1346, was consecrated to the apostles Saint-Peter and Saint-Paul. The construction of this chapel was a paramount concern for Clement VI. It seems that the finishing touches had to be accelerated to enable the pontiff to inaugurate it before his demise. He celebrated a service on All Saints' Day in 1352 before passing away on December 6 of the same year (Vingtain 1998, pp.220-222, p.396).

The result of the expansions of the Palais des Papes undertaken by Benedict XII and Clement VI have left a lasting legacy: a palace characterised by its complex and monumental architecture. Over time, it became a prominent reference in the realm of music, particularly in the practice of polyphonic ceremonial music. In this context, it appears to have been well-suited for the dissemination of political music, serving as a valuable tool for the pontiff during troubled times (Ferrando 2014b, pp.75-80).

Function of the chapels at the Palais des Papes

Based on their size and function in the liturgy, chapels were categorised into three distinct designations: *capella magna*, *capella parva*, or *capella secreta* (Schimmelpfennig 1991, p.100, p.107):

- The *capella magna*, or large chapel, was the principal venue for services designed to accommodate a substantial congregation. On major feast days, the public could attend

services presided over by the pope. This practice was evident in Benedict XII's chapel and later in the Great Chapel during the reign of Clement VI and his successors.

- The *capella parva*, or small chapel, was designated for daily services or as an auxiliary space during feast days when consecutive services were necessary. It also accommodated the Vespers of the day. The chapel of Saint-Martial could be associated with this designation.
- The *capella secreta*, or private chapel, situated near the pope's quarters, was a distinctive and exclusive space located near the pope's quarters. It was reserved for the pope and his close attendants, remaining generally off-limits to the public. The pope conducted Mass there, often with the assistance of a chaplain. While direct evidence of musical participation in its services is limited, a later testimony (Tomasello 1982, p.287) suggests the presence of singing during Masses celebrated by the schismatic Pope Benedict XIII, the final pope to reside in Avignon.

The Great Chapel: a venue for polyphonic singing

From the outset of his papacy, Clement VI introduced an unprecedented magnificence to his court, and the expansion of the papal palace under his directive allowed it to align with emerging theological and political requirements. This architectural augmentation served as a tangible validation of the papal legitimacy to reside in Avignon. Notably, the newly constructed papal chapel, the Great Chapel, played a pivotal role in hosting large-scale services, the *missa magna*, designed to accommodate numerous celebrants and a substantial congregation (Ferrando 2014b, p.87). Additionally, it held considerable significance in the musical pursuits of the palace, attracting composers, cantors, and musicians associated with the *Ars Nova* movement.

The cantors, constituting the esteemed body of *capellani capelle* under the guidance of the *magister capelle* and true experts in polyphonic compositions constructed in accordance with the principles of *Ars Nova*, were prominently featured in the Great Chapel. Their contributions played a vital role in the widespread dissemination of the papal message (Tomasello 1982, pp.1-2).

Architecture and decoration of the Great Chapel

The overall geometry of the modern-day Great Chapel closely resembles its original 14th century design (see Figure 4). It is a vast chapel with a parallelepiped shape, consisting of a single nave measuring 52 m long, 15 m wide, and 20 m high (total volume of 14,400 m³). The chapel exhibits an absence of regular columns or galleries, featuring surfaces crafted entirely from dense limestone, including the walls, floor, and ceiling. Comprising seven successive four-piece ribbed Gothic vaulted bays, it includes six identical bays, with an additional truncated bay on the eastern side. The eastern wall boasts two large, recessed windows, mirroring a similar arrangement on the western wall, and some bays incorporate recessed windows on the southern side. These windows were initially sealed with wax cloth during construction, which was subsequently replaced with stained glass. Engaged columns align with the vault ribs, providing separation between each bay and its neighbouring bays on both sides. Positioned adjacent to the second bay from the east is a side room known as the revestiarium, which functioned as a cloakroom for the pope to don liturgical vestments before religious services.

Arrangement, furnishing and decoration of the Great Chapel in the 14th century is extensively described by Colombe (1935). In the 14th century, the choir of the chapel - the sacred space consisting of the three easternmost bays - was separated from the rest of the

nave by a metal grill, called the *cancel*, and its floor was elevated by two steps. The altar in the first bay from the east was originally slightly separated from the eastern wall and was topped by a canopy. The second bay from the east contained the pope's throne, positioned against the northern wall and topped by another canopy. Adjacent to the throne were two individual seats for the cardinals seated alongside the pope. The third bay was known as the *parcus cantorum*, the space where the cantors performed. This space had wooden stalls against the two side walls, which also accommodated twelve cardinals on each side. It also housed lecterns decorated with the coat of arms of Clement VI and stools for the cantors and laypeople in front of the stalls.

In contrast to the contemporary Great Chapel, its medieval counterpart boasted a plethora of decorative elements. Historical inventory records attest to the acquisition of an extensive collection of carpets and tapestries sourced from Paris, and probably from Arras and Valenciennes (André-Michel 1917; André-Michel 1918). Among them, vibrant tapestries featuring hues of green and red adorned the lateral walls of the Great Chapel, covering a total length of 104 m. The wall behind the papal throne was particularly decorated with a cloth containing gold. These wall tapestries were affixed to wooden frames known as *planchettes*. Lavishly decorated pieces of cloth were placed atop the papal throne's seat, the cardinal seats, the altar, and the altar stairs. The floor of the choir was embellished with wool carpets, while woven mats made from straw and rush were used in the remainder of the chapel, covering a maximum surface area of 356 m². A virtual visual historical reconstruction of this period is shown in Figure 2.

It is plausible that these architectural and decorative attributes of the 14th century Great Chapel exerted an influence on its acoustics, subsequently impacting the production and dissemination of the polyphonic chant practised within its walls.

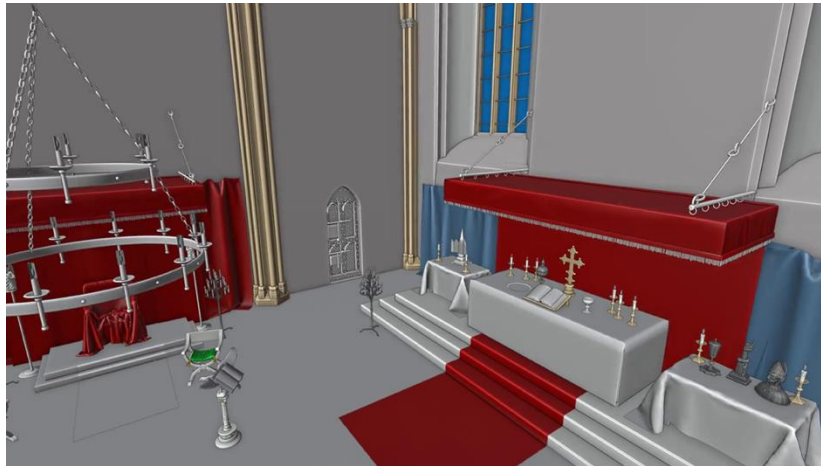


Figure 2. Partial reconstructed view of the choir of the Great Chapel with the furniture and tapestries from the 14th century in non-natural colours, showing the papal throne (left) and the altar (right). Source: Histopad/Palais des Papes.

Polyphonic singing and the Great Chapel

The musical repertoire performed in this setting encompassed either monodic Gregorian liturgy or more politically charged polyphony, exemplified by motets and Mass movements. Polyphonic compositions were regarded as powerful means for offering praises to patrons or asserting the legitimacy of the pope. The discourse set to music served as a form of public speech disseminated to audiences through the acoustics of the building (Ferrando 2014b; Ferrando 2015).

During the *Ars Nova* era, the motet was a prominent medium—a quintessential form of communication that reached many recipients and played a central role in various European courts. The motet is a multi-voiced musical form consisting of a *teneur* voice (the lowest

voice), a *duplum* (second voice), and a *triplum* (third voice), with music and text closely intertwined. Each voice could have a specific recipient (Ferrando 2014b): the *teneur* voice was intended for the secular world, the *duplum* voice for the ecclesiastical world (an intermediary between Heaven and Earth), and the *triplum* voice for the celestial realm (the divine realm).

Depending on the subject matter of the piece, the composer constructed the *teneur* based on an existing Gregorian chant that aligned with the liturgical calendar and could lend legitimacy to the new discourse. The higher voices, *duplum* and *triplum*, were then composed above the *teneur*, incorporating new texts, referred to as *tropes*, which were intended to be sung simultaneously. Composers skilfully employed musical techniques to allow motifs to “travel” between voices, which, combined with the layering of different texts, often results in a complex auditory experience for modern listeners. The art of organising the discourse of the motet according to both musical and textual argumentative structures stems from a writing technique known as *Ars Rhetorica Musicalis* (Ferrando 2006), which originated from the polyphonic repertoire of the Notre-Dame organum around the year 1200 (Billiet *et al.* 2022, Le Page *et al.* 2024).

While the motet remained the central form of *Ars Nova* polyphony, exemplified by the motet *Petre Clemens / Lugentium siccentur / Non est inventus*, which paid homage to Clement VI, polyphonic Mass movements were constructed in a similar manner. However, unlike the more flexible and free-standing nature of motets, Mass movements were tied to specific liturgical functions within the service, as they adhered to the fixed structure of the Mass Ordinary (e.g., *Kyrie, Gloria, Credo, Sanctus, Agnus Dei*), exemplified by the *Messe de Notre-Dame*. Manuscripts such as those of Apt and Ivrea (Kügler 2019) offer key examples of

both motets and Mass movements, illustrating the rich variety and complexity of this repertoire.

In summary, the motet, along with the polyphonic Mass movements, served as a testament to a distinctive political realm that, employing the art of persuasion, actively contributed to advancing its own agenda (Vecchione 2014).

Interplay between acoustics and intelligibility

The acoustic environment of the medieval Great Chapel likely impacted the intelligibility of the multi-voiced repertoires performed by the singers. Today, the chapel is quite different, with bare walls and a complete absence of decoration and furnishings. The connection between the architecture of a space and its acoustics - a crucial characteristic of spaces for musical creation - has been a subject of interest for many centuries (Katz and Wetherill 2005, De Muyenke *et al.* 2022a).

The earliest notions of architectural acoustics can be traced back to the writings of Vitruvius (Morgan, 1914, p. 132), who stated that sound propagates in a circular shape, like the waves caused by a stone cast in still water (called “undulatory” acoustics by Barbieri (2006)). Based on this concept, referencing ancient Greek authors, Vitruvius in the 1st century B.C.E. discussed four acoustic behaviours of reflecting sites (Vassilantonopoulos 2003):

- Acoustically dissonant (“kat-echountes”). This would be associated with prevalent diffusion or scattering.
- Reverberant (“peri-echountes”).
- Echoic (“anti-echountes”). This would be associated with noticeable, unwanted echoes.

- Acoustically consonant (“syn-echountes”). This would be associated with a supportive acoustic, beneficial reflections, being desirable for theatres.

Further discussions on evolutions of acoustic design can be found in Postma et al. (2021). Mainoldi (2001) explored how scholars from the Middle Ages understood the physics of sound and the art of music in general. As Vitruvius, Boethius (in *De Musica*) considered sound as a mechanical vibration propagating through the air, produced from a struck object, as a “continuous percussion of the air until it reaches the ear”⁶. Furthermore, the notion of “resonance” for medieval scholars, influenced by Aristotelian and Platonic ideas, might have conceptualised the harmonious blending or amplification of sound waves, possibly attributing it to the sympathetic vibrations of the elements or the divine order inherent in creation: “A clear, strong timbre, accompanied by resonance, will express to a greater degree the ethereal and ascending quality of the sound”, *i.e.* towards the divine, “while a multiple and confused ensemble of different timbres will evoke the chaos of raw matter and therefore its descending and disharmonious tendency”⁷. The resonance reflects the harmony and intelligibility of the sung texts, contrasting with the “formless chaos” of disharmony. Polyphony and the effort required to ensure intelligibility given a space’s acoustics represented a true sonic art in the service of understanding, reflecting the original etymological meaning of intelligence, *intellegere* - to comprehend.

⁶ “aeris percussio indissoluta usque ad auditum”, (Mainoldi 2001, p.217)

⁷ “Un timbro chiaro, forte e accompagnato da risonanza, esprimerà in maggior grado la qualità eterica e ascendente del suono, mentre un insieme molteplice e confuso di timbri diversi richiamerà la caoticità della materia prima e dunque la tendenza discendente e disarmonica di quello” (Mainoldi 2001, p.222)

Acoustic reconstruction of the Great Chapel

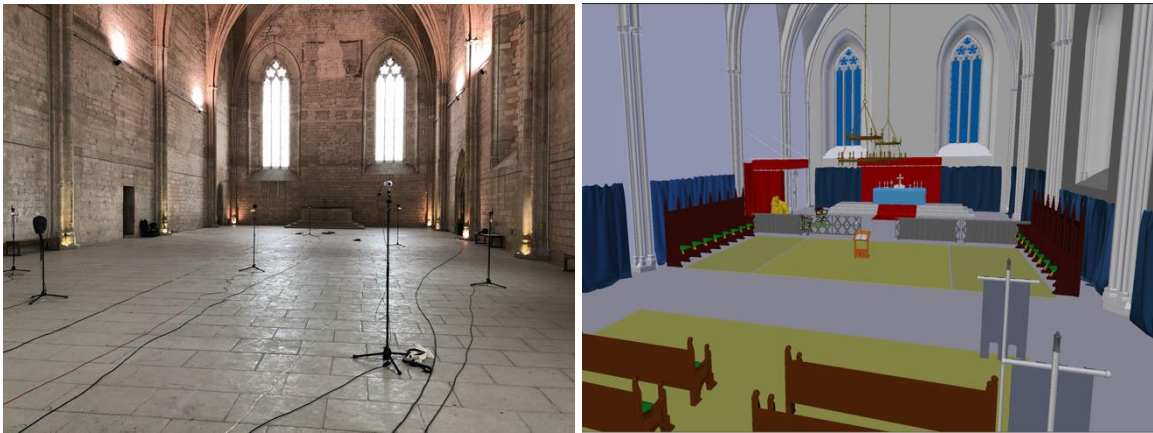


Figure 3. Images of the Great Chapel in the (left) modern state and (right) medieval state.

Source: (left) photograph of the in-situ RIR measurements by the authors, (right) visual model taken from Histovery - Histopad⁸ of the Palais des Papes/Avignon Tourisme.

Geometrical acoustic model

The acoustics of the Great Chapel was reconstructed through a calibrated geometrical acoustic (GA) model created within CATT-Acoustic/TUCT. A GA model is a polygonal mesh defining the interior surface of the room. Each element of the mesh is characterised by an acoustic material, which defines how much sound incident on the surface is absorbed, reflected, and scattered as a function of frequency. The process of acoustic calibration entails iterative adjustments of these material properties to attain comparable results with the real acoustics using acoustic metrics. This calibration is achieved by comparing acoustic metrics obtained from the model's outcomes with those from acoustic measurements conducted in the

⁸ Histopad of the Palais des Papes, <http://www.palais-des-papes.com/en/histopad-pour-tous/>, a mediation tool offering an Augmented Reality visit experience.

corresponding contemporary hall. Once calibrated, one can have strong confidence in the perceptual quality of the resulting simulations for various acoustic attributes (Postma and Katz 2016). Following the calibration procedure, the model can be modified to retroactively undo any geometrical or decorative modifications to the space at a certain moment in history, relying on the quality of the reference calibrated model and reasonable material definitions to achieve a historically informed virtual acoustic reconstruction (Postma and Katz 2015, Mullins *et al.* 2022, Mullins 2024, Ferrando and De Muynke 2024).

The GA model of the Great Chapel was used to numerically simulate the acoustic signature of the hall by generating room impulse responses (RIRs)⁹ in different conditions comprising two historical states (modern and medieval, see Figure 3). Generated RIRs were further used to create an immersive auditory environment for the singers who participated in the experiment, a process referred to as *room auralisation* (Kleiner *et al.* 1993). The consecutive steps leading to the creation of the calibrated GA model of the Great Chapel are described in the following.

In-situ acoustic measurements

In-situ RIR measurements were made in the contemporary Great Chapel (see Figure 3). These captured the acoustic response of the room for several receiver positions and source positions since acoustic responses are position dependent. A total of 64 source/receiver combinations were distributed along a grid in the Great Chapel. Those RIRs served for the analysis of the acoustic characteristics of the Great Chapel, but they could also serve for post-

⁹ An RIR characterizes the acoustic transformation the room impacts on a sound produced within, between a given source and a given receiver.

hoc auralisations from the same exact positions, even though that was not their primary purpose.

Geometric modelling

The geometry of the modern Great Chapel was designed with reference to an existing 3D graphical model of the chapel (see Figure 3) and a 3D laser scan point cloud obtained during the RIR measurements campaign.

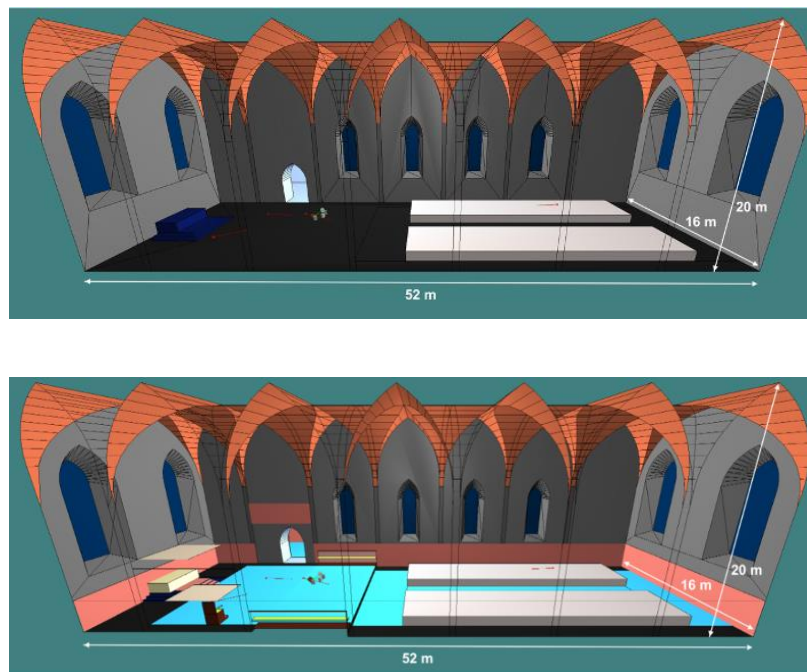


Figure 4. GA model of the Great Chapel in its (top) modern and (bottom) medieval states, where different colours depict different materials. The white blocks represent the audience congregated in the nave.

Acoustic calibration of the GA model

The acoustic properties of each surface material were first taken from published material databases, and later manually fine-tuned until the considered acoustic metrics fall within ± 1

JND¹⁰ around the measured values. The acoustic calibration was performed by comparing the simulated RIRs (generated using algorithm 1 of TUCT v2.0g with 800,000 rays and RIR length of 5 s) against RIRs measured on-site, following the calibration procedure elaborated by Postma and Katz (2015).

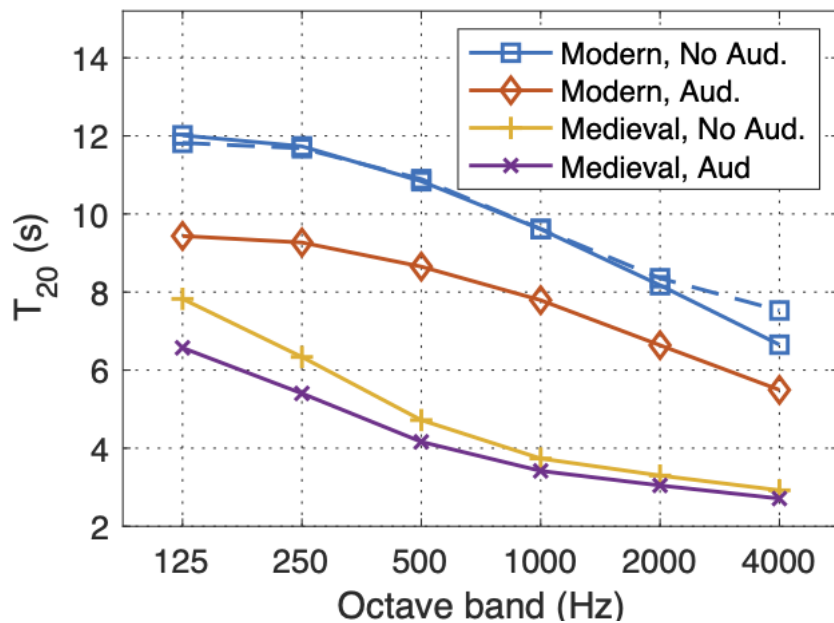
Time regression of the GA model

Despite its comparable geometry, the medieval Great Chapel exhibited significant damping attributed to various furnishing and decorative elements. These comprised extensive wall tapestries, rush matting on the floor, canopies above the altar and the pope's throne, wooden seating elements like stalls in the choir and pews in the nave for the congregation, as well as assorted pieces of cloth embellishing the altar, altar stairs, throne, and stalls. Figure 4 illustrates some of these elements through different colours, highlighting the contrast with the essentially empty space of the modern Great Chapel. The medieval GA model of the Great Chapel was derived from the modern calibrated GA model, subsequently refined using historical records documenting the interior furnishings and decorations from that specific period (Colombe 1935, p.15).

Acoustic characteristics of the Great Chapel

¹⁰ The Just Noticeable Difference of a metric, abbreviated JND, is its smallest detectable variation. It is based on previous studies in the literature and reported in standards.

Due to the absence of significant absorbing surfaces, the modern Great Chapel exhibits a high level of reverberation. As depicted in Figure 5, T_{20}^{11} approaches approximately 12 s in the lowest frequency bands when no audience is present. The acoustics of a room can be significantly influenced by the presence of an audience and the occupancy density. For this study, a relatively large audience seated on pews in the nave, which would likely have been the case during papal masses, was simulated. For consistency in the study of changes relative to decoration and architecture, the audience occupies the same surface area and maintains the same occupancy rate in both modelled historical states of the building. The presence of an audience tends to reduce the reverberation time compared to the empty configuration. Figure 5 illustrates the reverberation times in both simulated states of the building, with and without the inclusion of an audience.



¹¹ T_{20} is a standard measure of the reverberation time of a room, in seconds (ISO 3382-1 2009). It indicates the time it takes for an impulsive sound to decay by a factor of 1000 (i.e., 60 dB), extrapolated from analysis of a 20 dB decay from 5 dB below the direct sound. JND = 5 %.

Figure 5. Estimated T_{20} (reverberation time) across different frequency bands, calculated by averaging measurements from sixteen evenly spaced positions within the Great Chapel.

The graph shows the T_{20} values for the modern, with and without audience occupation.

Measured values are represented by the dashed line (- - -) and various modelled values depicted by solid lines (—).

Singing experiment

The goal of the experiment was to evaluate how different room acoustics affect musical performance. *Diabolus in Musica*, a small conducted vocal ensemble consisting of four male singers (one bass, one baritone, and two altos) trained in medieval performance techniques and familiar with the acoustics of the Great Chapel in its modern state, took part in this experiment.¹²

Virtual Acoustic Environments

The acoustics of the Great Chapel were rendered through RIRs simulated via Virtual Acoustic Environments (VAEs), *i.e.*, via the GA model of the Great Chapel under different conditions. In addition to the acoustic characteristics of the room, RIRs also depend on the position of the sources and receivers used in the simulations¹³. Consequently, some decisions had to be made on the position of the choir as well as on the physical distribution of the

¹² The musicians - Philippe Roche (Bass), Emmanuel Bocquet (Baritone), Raphaël Boulay (Tenor 1), and Olivier Germond (Tenor 2) - formed the test group. The ensemble was directed in certain polyphonic pieces by the conductor and artistic director, Antoine Guerber.

¹³ Each singer is represented by both a source (mouth) and a receiver (pair of ears) positioned 15 centimeters away from each other (nearly co-located source-receiver pairs), whereas the conductor was included as a receiver only.

singers. Evidence of possible positions and arrangements of the singers in the Great Chapel in medieval times was first investigated. Two arrangements were considered based on iconographic collections of fresco by Matteo Giovannetti from St Martial chapel shown in Figure 6: a semi-circular arrangement and two staggered rows.



Figure 6. (left) Angels in a semi-circular arrangement and (right) cantors positioned in a staggered formation. Frescoes by Matteo Giovanetti in the chapel of Saint-Martial. Source: photographs by the authors.

Two positions of the choir in the chapel were considered, both in the *parcus cantorum* area, *i.e.*, between the stalls. The most obvious position is on the symmetry axis of the chapel, equidistant from either stall, right below the centre of the vault. However, the historical authenticity of that position may be discussed since the singers would then obstruct the view of the celebrant at the altar as seen from the assembly. Consequently, a position closer to the southern stalls was also considered.

In summary, the acoustics of the Great Chapel were rendered with the following variable conditions:

Room: either modern state of the Great Chapel (modern) or medieval state, ca. 1362 (medieval).

Position of the ensemble in the chapel: in the *parcus cantorum*, either on the symmetry axis of the chapel (on-axis) or shifted towards the southern stalls (off-axis), as illustrated in Figure 7.

Arrangement of the singers: either arranged semi-circularly (arc) or in 2 staggered rows (staggered), as illustrated in Figure 7.

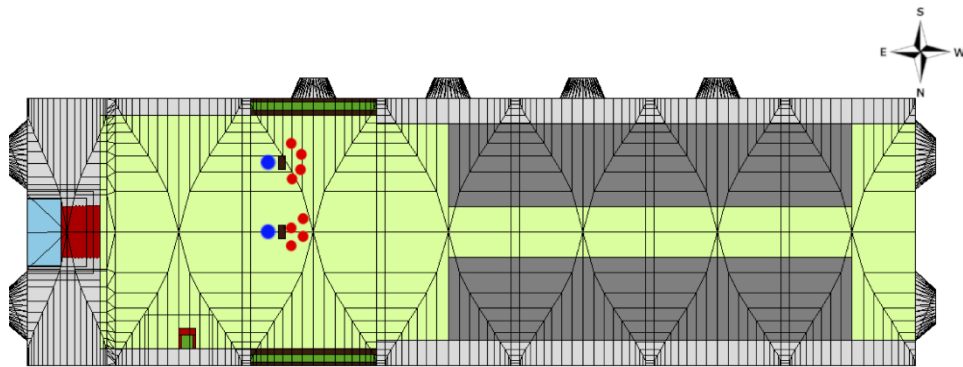


Figure 7. Overhead plan view of the medieval state model illustrating the positions of singers (red dots), conductor (blue dots), and lectern (brown rectangles). The image highlights two specific *position/arrangement* combinations: (upper) off-axis/arc and (lower) on-axis/staggered.

In the arc *arrangement*, the singers were evenly positioned along an arc of a circle with a span of 120 degrees and a radius of 1.2 m. In the staggered *arrangement*, the singers were distributed in two staggered rows, with two singers in the front row and two singers in the back row, shifted laterally by half the distance between two consecutive singers, as illustrated in Figure 7. During the experiments, the physical placement of the singers matched the simulated *arrangement* condition, such that their actual positioning in the experimental room always corresponded to the virtual *arrangement* simulated in the corresponding VAE, whether it was arc or staggered.

In the GA model, the sources were simulated with a singing voice directivity pattern, directed towards a virtual lectern positioned between the singers and conductor (see Figure 7), as if the singers were looking at a collective music score placed on the lectern. The conductor's listening position faced the singers, situated on the opposite side of the lectern¹⁴. Based on the hypothesis that during performances singers in a conducted ensemble typically focus on the conductor and do not rotate their head much, the decision was made to render the VAEs with a fixed head orientation, disregarding actual rotational movements of the singers' head during performance. Consequently, the VAEs were rendered using static orientation non-individual Binaural Room Impulse Responses (BRIRs), *i.e.*, impulse responses from each source position to each listener's left and right ears with a fixed head orientation.

For the interactive singing experiment, BRIRs were calculated with 1,000,000 rays, utilising algorithm 1 of TUCT v2.0g. The length of the BRIRs was limited based on the T_{20} values of occupied room states presented in Figure 5, resulting in a maximum duration of 10 s for the modern *room* and 8 s for the medieval *room*.

Experimental setup

¹⁴ In choirs, the role of fully-fledged conductor member is a modern habit. In medieval times, most often one of the singers was conducting the rest of the choir while singing.



Figure 8. Photograph of the singers during the experiment, in the *arc* arrangement, in the anechoic room. Source: photograph by the authors.

The experiment aimed to capture the natural singing of each individual singer in a realistic ensemble configuration within the auralised virtual acoustics of the Great Chapel. For that purpose, the experiment took place in a semi-anechoic room (PRISM laboratory) as shown in Figure 8, to eliminate any room reflections or reverberation. Each singer wore a head-worn proximity microphone (DPA 4088, cardioid pattern) to minimise crosstalk from other singers, and open-back headphones (Sennheiser HD650) that allowed them to hear their voices within the auralised virtual acoustics of the Great Chapel. The singing captured by the close-mics was recorded along with the singers' head motion during the performance, using a motion capture system for future analysis. Open-back headphones were used to allow for the contribution of the naturally arriving direct sound, i.e. propagating through the air, and that of the reverberated voice signals reproduced through headphones. The protocol of this study was based on earlier comparative works (Eley *et al.* 2021).

Although open-back headphones are generally more acoustically transparent than closed-back headphones, different models of open-back headphones exhibit different levels of acoustic transparency (Mülleder *et al.* 2023). A higher degree of acoustic transparency leaves the transmitted sound less affected when passing through the headphones, hence it may yield a better balance between direct and reverberated sounds.

Auralisation engine

BRIRs were generated without the direct sound component for each combination of singer pairs. This resulted in a 4×4 matrix of BRIRs, as depicted in Figure 9. The auralisation architecture, implemented in MaxMSP¹⁵, was designed for real-time processing. Apart from the 16 BRIRs dedicated to the singers, an additional set of 4 BRIRs without the direct sound component were produced for auralising the 4 singers at the conductor's listening position. The system was configured with an internal audio buffer size of 64 samples at a 48 kHz sampling rate, resulting in an I/O delay of 1.3 milliseconds without any artefacts for the 40 independent convolutions required ($((4 \times 4 \text{ singers}) + [4 \text{ singers at the conductor}]) \times 2$ channels). To achieve proper time synchronisation between the naturally arriving direct sound and the rendered reverberated sound reproduced over headphones, the 64 leading zeroes in the BRIRs were removed, compensating for the I/O delay.

¹⁵ What is Max?, <https://cyclling74.com/products/max>

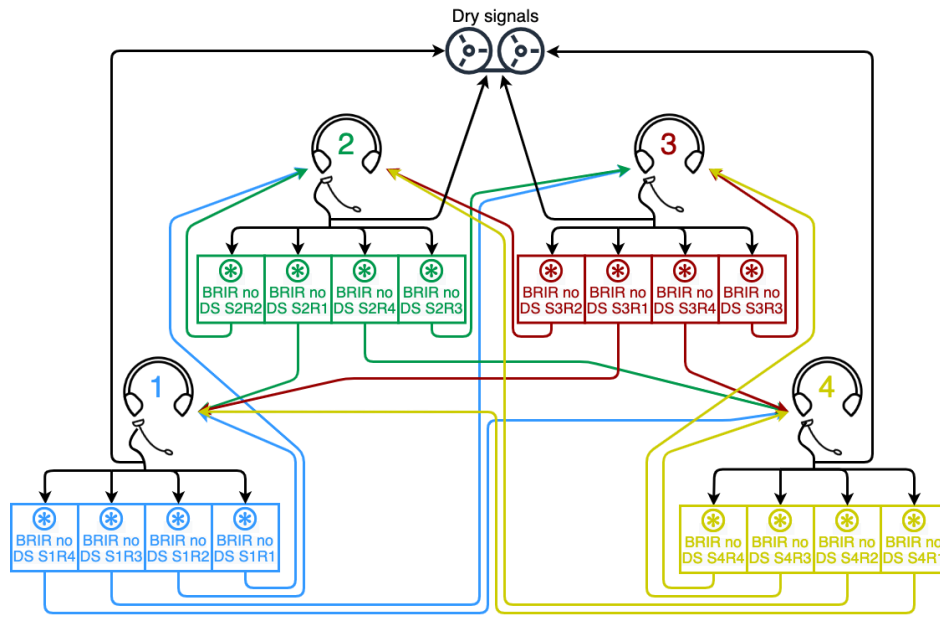


Figure 9. Block diagram of the auralisation system and recording of the dry signals. ‘ \otimes ’ represents the convolution operation. ‘BRIR no DS’ stands for ‘BRIR without direct sound’, and ‘ S_iR_j ’ stands for Source i to Receiver j . The conductor’s signal path is not shown.

Calibration of the auralisation system

Level calibration of the simulated acoustics relative to the naturally arriving direct sound of the singers is crucial to achieving ecologically valid performances. Initially proposed by Eley *et al.* (2021) for loudspeaker reproduction and later detailed in Mullins and Katz (2023), the calibration protocol employed is summarised here.

A two-step calibration procedure of the auralisation system was conducted by successively adjusting the playback level and the singer microphone gains. The calibration procedure ensured both a natural balance between direct and reverberated sounds for each individual singer as well as a well-balanced inter-singer reproduction level.

Playback level adjustment

Prior to the experiment, the playback level of the auralisation system, *i.e.* the headphone preamp gain, was adjusted based on a comparison between reference and measured values of an adapted ST_{late} acoustic metric. ST_{late} was chosen as it measures the balance between early sound energy (within the first 10 ms after the direct sound) and late sound energy (between 100 ms and 1 s after the direct sound) during a performance in a given room. ST_{late} calculation is formalised in Eq. 1 where $h(t)$ denotes the impulse response between the source and receiver in the given room¹⁶.

$$ST_{late} = 10 \log_{10} \left(\frac{\int_{100ms}^{1000ms} h^2(t) dt}{\int_{0ms}^{10ms} h^2(t) dt} \right) \quad (\text{Eq.1})$$

As a standardised room acoustic parameter, ST_{late} is typically measured with an omnidirectional source and an omnidirectional receiver positioned 1 m apart (ISO 3382-1 2009). For this calibration protocol, it was adapted to the specific needs of the study, being measured with a source of appropriate directivity and a binaural receiver positioned 1 m apart. Similarly adapted ST_{late} of a BRIR with the direct sound included and generated with the calibrated GA model with a receiver placed at 1 m in front of a source having a voice directivity pattern was used as reference. Although these adapted ST_{late} values should not be directly compared to published ST_{late} values presented in literature, this approach remains valid as they are only meant to be compared against a reference value of adapted ST_{late} .

¹⁶ In the acoustic scenarios considered in the experiment, early sound energy arriving within the first 10 ms after the direct sound contains the direct sound and the floor reflection only.

As shown in Figure 10, a similar scenario was reproduced in the experimental room to obtain adapted ST_{late} values to be compared against the reference: the head-worn microphone (DPA 4088) was placed right in front of a loudspeaker (Genelec 8020) at a distance representative of the mouth-microphone distance in a real singing situation (5 cm), and an artificial head (Neumann KU100) wearing a pair of headphones (Sennheiser HD650) was positioned at 1 m in front of the loudspeaker.



Figure 10. Acoustic source (loudspeaker with head-worn microphone 5 cm apart) and receiver (artificial head wearing headphones) located 1 m apart in the experimental room, used for the adjustment of the auralisation system playback level. Source: photograph by the authors.

With the auralisation system running, an impulse played back through the loudspeaker was recorded with the artificial head, including the naturally arriving direct sound passing through the open-back headphones and the reverberated sound reproduced by the headphones. This

yielded a measured value of adapted ST_{late} further compared to the reference adapted ST_{late} . The headphones preamp gain was iteratively adjusted, thereby adjusting the level of the reverberated sound while maintaining the level of the naturally arriving direct sound constant, until the measured adapted ST_{late} matched the reference adapted ST_{late} . The playback level resulting from this first calibration step was applied equally for each individual singer, thereby ensuring for each of them a good balance between reverberated sound and naturally arriving direct sound for a nominal mouth-microphone distance of 5 cm.

Microphone gain adjustment

Before each experimental session, any mouth-microphone deviation from the nominal distance was compensated for by an individual calibration of the microphone gain for each singer. Once all microphone gains were adjusted, it further ensured a well-balanced inter-singer reproduction level. In practice, prior to the experiment, a position was chosen on the experimental stage for the test source (Genelec 8020 loudspeaker equipped with DPA 4088 head-worn microphone) and another position was chosen in front of the experimental stage for a SPL meter. The acoustic level in dB(A) of a test signal reproduced by the test source was measured by the SPL meter and paired with the level in A-weighted dBFS picked-up by the head-worn microphone, providing reference paired-values. This approach allows to associate a pick-up level (A-weighted dBFS) for a nominal mouth-microphone distance to an acoustic level (dB(A)) at a known distance from the source, thereby allowing for further compensation of the deviation from the nominal distance. At the beginning of each singing session, these paired-values were measured for each individual singer wearing their individual microphone and compared against the reference paired values, with the source and SPL meter located in the same chosen positions.

The reference paired values were obtained by playing back a pure tone of constant level through the loudspeaker. At the beginning of each singing session, each singer was asked to stand in the chosen source position on stage and to sing a sustained note with a constant level while wearing the head-worn microphone. The resulting acoustic level measured by the SPL meter was noted while the sung note was recorded through the microphone. The RMS value was calculated in A-weighted dBFS on a selected 1 s time-window of the recorded signal filtered through an A-weighting filter. The obtained paired-values were then compared against the reference paired-values, and a resulting compensation gain was applied to the microphone input for each individual singer.

For example, let us assume that the reference acoustic level was measured at 80 dB(A) and that the paired reference microphone pick-up level was measured at -12 dBFS (for a nominal mouth-microphone distance of 5 cm). Before a singing session, the acoustic level of a sustained note sung by a singer is measured at 83 dB(A) while his microphone pick-up level is measured at -15 dBFS. The measured acoustic level is 3 dB(A) higher than the reference acoustic level, and so should be the measured microphone pick-up level compared to the reference microphone pick-up level, that is -9 dBFS. Consequently, a 6 dB compensation gain will be applied to his microphone, aiming at compensating for the greater distance between his microphone and his mouth compared to the nominal one.

Musical repertoire

A collaborative effort with the singing ensemble led to the selection of a corpus of five music pieces for the experiment, containing examples of polyphonic and monophonic chant. The repertoire was chosen because of its contemporaneity with the considered time era (ca. 1362) and its diversity in terms of compositional techniques and connections to the papacy

and ceremonial events. The motet *Petre Clemens* by Philippe de Vitry, and the following pieces by unknown authors: *Kyrie Rex Angelorum*, *Kyrie de Fronciaco*, *Credo Bombarde*, *Aurea Luce*, and the intonation *Dominus Vobiscum*, were chosen. They were drawn from two musical programs, *Missa Magna* and *Cantores*, designed and already performed by the ensemble in the modern acoustics of the Great Chapel during concerts. For the concerts, the ensemble was positioned in the *parcus cantorum* (third bay from the east) against the southern wall of the Great Chapel.¹⁷

Experimental protocol

The sessions were organised by condition, where each session simulated a particular combination of the variable conditions *room*, *position*, and *arrangement*. During each session, the selected music pieces were interleaved to create a group of pieces that were repeated consecutively three times, resulting in an individual session duration of approximately 30 min. Singers were not informed about the specific conditions of the VAEs, ensuring that their responses were based solely on their perception.

Following each session, participants (singers and conductor) were asked to complete a questionnaire, providing their impressions during that session. The objective of the questionnaire was to evaluate how the different conditions affected their perception of their own performance and the performance space. The questionnaire consisted of explicit questions accompanied by a scoring system to provide assessments. Additionally, they had the opportunity to leave spontaneous comments and feedback. After conducting a preliminary

¹⁷ Example auralisations of the choir singing in both medieval and modern room configurations, for various listener positions, are available at <https://soundcloud.com/user-562474223/sets> (last viewed 21-01-2025).

analysis of the questionnaire, certain trends were identified. Analysis of the questionnaire has been previously presented (De Muynke *et al.* 2022b, Katz *et al.* 2024), and will not be presented here for brevity.

Diabolus in Musica: an ensemble specialising in historically informed medieval music

Diabolus in Musica was initially formed by Antoine Guerber, the conductor and artistic director of the ensemble from 1991 to 2021. It gradually came together around a core group of singers, mostly from ensembles such as Organum (Marcel Pères) or Gilles Binchois (Dominique Velard). This ensemble gained increasing recognition through recordings, gradually establishing a significant reputation. However, the ensemble had no experience with studio recording as it is not customary for this type of repertoire to record outside of natural acoustic performance settings. Thus, the singers were not familiar with using monitoring headphones during recording sessions. Recordings are usually planned with coherence to the selected program. For instance, the choice of the Fontevraud Abbey and its abbey church was made for recording religious repertoire. For secular repertoire, such as Guillaume Dufay's songs, the grange of Villefavard, with its drier acoustics, was selected. In 1999, the ensemble recorded the *Missa Magna* program based on pieces associated with the Great Chapel of the Palais des Papes. This program was notable for reproducing a large-scale Mass historically sung in the pontifical chapel. In addition to reconstructing the scores from the Ivrea and Apt codices, the pronunciation of Latin “à la française” was a novel aspect of this interpretation. The recording was situated in Fontevraud Abbey. The program was also performed in concert at the Palais des Papes in May 2002 in the Grand Tinel hall (Figure 1, item 5, first floor). At that time, most concerts were performed in the Grand Tinel Hall, as the Great Chapel was usually considered unsuitable for musical performances. However, the

encore performance was situated in the Great Chapel, shedding light on its acoustics. In 2016, Diabolus in Musica performed a concert in the Great Chapel for the *Cantores* program, focusing on the Masses of Apt and political motets dedicated to Clement VI. This gradual awareness of the importance of the historical acoustics of the production venue was the impetus at the origins of this current study. Moreover, Diabolus in Musica's familiarity with the modern acoustics of the Great Chapel logically led to the ensemble's inclusion in the experimental design and preliminary testing.

Insights from the singing experiment: Feedback and reflections

Complementing the questionnaire, individual interviews were conducted with the participants at the end of various singing sessions to gather their self-impressions of their vocal performance in the immersive auralisation setup. Additionally, a final group interview with all the musicians was held at the end of the experiment to encourage inter-musician exchange and provide a collective reflection on the experience.

It should be noted that the goal of this study was not to conduct a comprehensive anthropological investigation but rather to collect the singers' immediate feedback as practitioners on the abilities and limitations of the proposed auralisation system in offering acoustic conditions suitable for ensemble vocal performance. Furthermore, the study sought to inspire broader reflections on musical interpretation in alignment with the acoustics of a given space.

Novelty of the singing experience

The conductor described the experience as “a novel and exciting experience that allowed stepping outside the realm of fantasy.” For him, it represented “a fantastic dialogue between

the past and the present”, while the first tenor considered the shared immersion “an unprecedented experience, a kind of time bridge.” The bass noted that the medieval acoustics reproduced through the auralisation system enabled him to feel “a real change of place and time,” even in the blind test conditions. He emphasised how his profession as a singer involves constant adaptation to different acoustic environments, which was particularly relevant in this experiment. Reflecting on his experience, he explained that the discovery of the medieval acoustics of the Great Chapel has prompted new reflections on constructing vocal gestures within historically informed and reconstructed acoustics – a completely new aspect of his vocal practice. Collectively, the singers expressed enthusiasm for the immersive setup and its potential to connect them to the past acoustic condition of a performance space.

Challenges in the experimental setup

The singers’ feedback revealed several challenges associated with the overall unnaturalness of the immersive singing setup. One prominent issue was the disruption of physical and sensory references, particularly concerning the body’s placement within the simulated sound environment. For instance, the headphones were perceived as an element that interfered with the singers’ connection to their body and resonators, which are central to sound emission¹⁸. The first tenor provided detailed feedback about the negative sensations caused by the setup, specifically highlighting a lack of visual reference correlated with his spatial placement in the sound environment. He described a disconnect between what he saw in front of him and what he heard in the simulation, which created a destabilising sensation

¹⁸ In typical early music discographic recordings, headphones are often avoided, and singers perform in natural acoustic environments. This practice may explain some of the challenges faced by the singers during the experiment.

akin to being in an artificial “bubble.” Adapting to this setup required significant effort, which he compared to “adjusting to zero gravity” over the course of a day.

The first tenor further observed that “the filtering effect of the headphones” altered the “auditory feedback he was accustomed to”¹⁹, impacting his perception of both his voice and the group’s balance. Although these sensations gradually diminished as the singers acclimatised to the setup, responses varied significantly based on individual sensitivities. For instance, both the second tenor and the bass described the setup as fatiguing, particularly toward the end of the day. This fatigue, often described as a sensation of “cotton in the ears,” differed in intensity and persistence among the singers.

The bass additionally noted the difficulty of transitioning between the modern and medieval space models, as the abrupt changes required him to prepare his voice in a real acoustic environment outside the auralisation setup to maintain vocal stability. For the first tenor, however, constructing vocal gestures did not necessarily depend on actively listening to the acoustics. Instead, his initial focus was on his own sound construction and direct adjustments with the other singers, a primary step after which he could turn his attention to the acoustics themselves.

¹⁹ Prior to the experimental design, it was anticipated that the use of headphones during singing might be inconvenient or disruptive for some singers. Reflections were made on the type of headphones that would ensure the musicians’ comfort while also fulfilling the requirements for crosstalk minimisation during the recordings, ultimately leading to the choice of open-back headphones, which were considered suitable for allowing the singers to remain sufficiently interconnected.

Impact of simulated acoustic conditions on interpretation

The simulated acoustic conditions, including both the historical states of the Great Chapel and the spatial arrangements of the singers, had a significant impact on their interpretation. Feedback from the singers revealed clear preferences and insights into how these conditions shaped their experience.

The medieval acoustic arrangement of the chapel was generally well-received by the singers. They reported finding mutual listening more straightforward compared to the modern acoustics, which made performing polyphonic pieces easier. This may be attributed to the drier acoustics of the medieval Great Chapel, which allowed for more intuitive vocal gestures. Singers noted a decreased need to “push the voice” in this setting, particularly benefiting the bass, who found a better balance with the other three voices compared to the modern acoustics.

Transitioning to the broader implications of these acoustics, singers observed that the simulated medieval acoustics demanded significantly greater precision in sound construction and intonation. Unlike the modern acoustics, whose longer reverberation tended to mask small inaccuracies and encourage a degree of passivity, the medieval acoustics required active and focused engagement. As one singer remarked, the modern acoustics were “less demanding” due to the forgiving nature of the longer reverberation, while the medieval acoustics, with their clearer and more defined sound, exposed even minor imperfections. This necessitated more intensive training and precision to achieve a high-quality performance.

In addition to the historical states of the acoustics, the singers provided feedback on their spatial arrangements within the setup. While individual preferences emerged, there was general agreement on several key aspects. Regarding Gregorian pieces, the *staggered*

arrangement was particularly appreciated for its ability to facilitate the construction of a common vocal gesture for Gregorian monody. The side-by-side listening inherent to this arrangement was described as “much more comfortable”²⁰ and provided a fresh approach to interpreting Gregorian chant compared to the traditionally utilised *arc* arrangement.

Together, the feedback on the historical acoustic states and the spatial arrangements underscores the critical role of simulated acoustic conditions in shaping both individual performance techniques and ensemble interpretations. These insights highlight the intricate interplay between performance space acoustics and musical interpretation, particularly in historically informed contexts.

Broader Reflections on Musical Interpretation and Aesthetic Insights

The immersive experience with the reconstructed medieval acoustics led the singers to profound reflections on musical interpretation, vocal techniques, and the aesthetic understanding of medieval repertoire. They observed that the medieval acoustics demanded greater precision and attentiveness, as the transition from a familiar space to a reconstructed one imposed a more demanding approach to mutual listening and vocal production. The bass emphasised that interpreting early music involves musicological exploration, and this experiment reinforced the importance of considering historical acoustics when engaging with scores and historical sources.

Moreover, the singers commented on the aesthetic and ensemble dynamics influenced by the medieval acoustics. The reduced reverberation left more space for interpretative details,

²⁰ On average, the singers are closer to one another in the *staggered* arrangement ($0.73 \text{ m} \pm 0.22 \text{ m}$) than in the *arc* arrangement ($1.27 \text{ m} \pm 0.53 \text{ m}$), which probably contributes to improve the mutual listening.

as one singer described, finding the medieval room “musically more satisfying.” Others appreciated the improved ability to hear each other, particularly in achieving a more balanced blend between the two highest voices, which enhanced the ensemble’s overall interpretation. These insights suggest that the reconstructed medieval acoustics could inspire new aesthetic approaches to medieval singing, challenging the traditional emphasis on highly reverberant environments.

The potential for advancing musicological understanding was also recognised. The singers’ feedback demonstrates the value of the auralisation system in exploring historical acoustic contexts. They described it as an opportunity to connect with the acoustics of the 14th-century pontifical chapel, aiding in refining historically informed performance practices. As ongoing objective analyses of the recorded performances continue, they promise to reveal further insights into the relationship between acoustics, vocal production, and the interpretation of medieval repertoire.

Overall, the singers’ experiences highlight the system’s ability to recreate the acoustic conditions encountered by musicians in the 14th-century pontifical chapel. This elicited reactions from the ensemble that constitute a key outcome of the study, particularly in exploring how such acoustic reconstructions can contribute to both historical understanding and modern interpretations of early music.

Conclusion

This paper presented an interdisciplinary study bridging medieval musicology and room acoustics, focusing on the virtual reconstruction of the acoustics of the Great Chapel of the Palais des Papes in Avignon in two historical states. These reconstructions were auralised for singers from a vocal ensemble specialising in medieval repertoire during a laboratory-based

singing experiment. The study explored the impact of these reconstructed acoustics on vocal gesture in a historically informed context, particularly for the *Ars Nova* repertoire of the 14th century and earlier Gregorian chant.

The feedback collected through questionnaires and interviews provided valuable insights into the benefits and limitations of the auralisation system. Singers highlighted the novelty of performing in the medieval acoustics, describing it as a unique opportunity for historically informed musicological exploration. They also expressed preferences regarding the increased adequacy of the medieval acoustics and specific physical choir arrangements for the interpretation of certain musical repertoires. However, wearing headphones posed challenges, likely worsened by their limited acoustic transparency, making the experimental conditions less natural than typical singing situations. Recent advancements, such as the adoption of an alternate style of open-back headphones have mitigated some of these limitations (Mullins and Katz 2023). Future objective analysis of the recorded performance will investigate the impact of the acoustics and spatial arrangement on musical interpretation across different repertoire.

The ability to virtually reconstruct heritage acoustics in historical states offers significant potential for both early music interpretation and cultural mediation (Peichert *et al.* 2022, 2024, Katz *et al.* 2024). For example, vocal recordings spatialised within the medieval acoustics of the Great Chapel could be incorporated into the planned *Ars Musica* audio-guided tour at the Palais des Papes. This prospective tour envisions a partial reconstruction of a ceremonial event from the time of Popes Clement VI and Innocent VI, providing an immersive sensory experience. As discussed by Grassin (2022), such an approach could

enable wider audiences to connect with the history of the Palais des Papes through a dynamic and engaging presentation of *Ars Nova* music.

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List of references

André-Michel, R. 1917. Le Palais des Papes d'Avignon. Documents inédits. *Annales d'Avignon et du Comtat Venaissin* 5: 1-16 and 124 (part I).

André-Michel, R. 1918. Le Palais des Papes d'Avignon. Documents inédits. *Annales d'Avignon et du Comtat Venaissin* 6: 3-24 (part II).

Anheim, É. 2008. La musique polyphonique à la cour des papes au XIV^{ème} siècle. Une sociologie historique. In *Bulletin du centre d'études médiévales d'Auxerre / BUCEMA*, Special Issue 2, *Le Moyen Âge vu d'ailleurs* 7: 3-4.

²¹ <https://www.mmsh.fr/>

²² <https://avignon-tourisme.com/en/>

²³ <https://www.diabolusinmusica.fr/>

²⁴ <http://phe.pasthasears.eu>

- Barbieri, P. 2006. The state of architectural acoustics in the late Renaissance. In *Architettura e Musica Nella Venezia del Rinascimento*; Howard, D., Moretti, L., Eds.; Bruno Mondadori: Milan, Italy: 53–78.
- Billiet, F., V. Le Page, S.S. Mullins, and B.F.G Katz. 2022. Virtual acoustic reconstructions of Notre-Dame cathedral's past for musicological study. At *Music and contexts in the Iberian world medieval and renaissance (MEDyREN): Early Music, Architectural Spaces and New Technologies*, May 2022.
- Le Page, V., S. S. Mullins, B. F. G. Katz, and F. Billiet. 2024. Virtual Acoustic Reconstruction of Notre Dame Cathedral's Choral Past, ch. 6, Esteve, Eva / Griffiths, John / Rodilla, Francisco (Ed.), *Historical Resonances: Space, Senses and Early Music*, pp. 129–150. Leiden: Brill, 2024, doi:10.30965/9783846769133_007.
- Colombe, G. 1935. Au Palais des Papes: la chapelle Clémentine vue de l'intérieur. In *Mémoires de l'Académie de Vaucluse 1935*. Paris: E. Champion.
- De Loye, G. 1988. Réception du pape Clément VI par les cardinaux Hannibal de Ceccano et Pedro Gomez à Gentilly et Montfavet, 30 avril-1er mai 1343 (ou 1348). In *Avignon au Moyen Âge, textes & documents*, ed. H. Aliquot, and B. Guillemain, 81-92. Avignon: Aubanel.
- De Mynke, J., M. Baltazar, M. Monferran, C. Voisenat, B.F.G. Katz. 2022a. Ears of the past, an inquiry into the sonic memory of the acoustics of Notre-Dame before the fire of 2019. In *Journal of Cultural Heritage*, 56:130-137. doi:10.1016/j.culher.2022.09.006.
- De Mynke, J., N. Eley, J. Ferrando, and B.F.G. Katz. 2022b. Preliminary analysis of vocal ensemble performances in real-time historical auralizations of the Palais des Papes. In *Proceedings of the Symposium on The Acoustics of Ancient Theatres*, Verona, 1–4.
- Eley, N., S.S. Mullins, P. Stitt, and B.F.G Katz. 2021. Virtual Notre-Dame: Preliminary results of real-time auralization with choir members. In *Proceedings of the International Conference on 3D Audio (I3DA)*, 1–6. doi:10.1109/I3DA48870.2021.9610851.

- Ferrando, J. 2006. L'Ars Rhetorica Musicalis en Avignon au temps des papes: L'exemple du motet Petre Clemens de Philippe de Vitry (1342). In *Proceedings from ICMS 7*, Acta Semiotica Fennica n°XXIII, ed. E. Tarasti, 810-813.
- Ferrando, J. 2007. Musique et société en Avignon, L'art musical au service de la théocratie de Clément VI:: Le cas du Petre Clemens / Lugentium siccentur / Non est inventus de Philippe de Vitry. PhD diss., Université de Provence, Aix-Marseille I.
- Ferrando, J. 2014a. « Semper favenant operi », Le motet Petre Clemens / Lugentium siccentur / Non est inventus. Une production musicale au service de la légitimité pontificale. In *Roda da Fortuna*, 2 170-190.
- Ferrando, J. 2014b. Solus Deus creat nullum corpus potest creare, La Chapelle Saint-Pierre / Saint-Paul du Palais des Papes, une projection architecturale du motet Petre Clemens ? In *Ontologie de la création en musique*, ed. C. Esclapez, 3, 10-21. Paris: l'Harmattan. ISBN: 978-2-343-04991-5.
- Ferrando, J. 2015. Music, Architecture and Symbolism in the court of Clement VI: another interpretation of the pontifical Policy in Avignon. In *Choir Stalls in Architecture and Architecture in Choir Stalls*, ed. F. Villaseñor Sebastián, M.D. Teijeira Pablos, W. Muller, and F. Billiet, 116-126. Cambridge: Cambridge Scholars Publishing.
- Ferrando, J. 2020. Comprendre le geste musical patrimonial: le projet IMAPI. In *Scénographies numériques du patrimoine*, ed. J. Deramond, J. De Biberan, and P. Fraysse, 67-101. Avignon: Éditions Universitaires d'Avignon.
- Ferrando, J. 2022. Interprétation Musicale en Acoustique Patrimoniale Immersive (IMAPI): Patrimoines en Médiation. In *Actes des Rencontres Nationales sur les Recherches sur la musique*, 101-108. Paris: Collegium Musicae.
- Ferrando, J., and J. De Muynke. 2024. Interpretation of a Medieval Vocal Repertoire in the Reconstructed Acoustics of the Great Chapel of the Palais des Papes. In *Historical Resonances: Space, Senses and Early Music*, E. Esteve Roldán, J. Griffiths and Francisco José Rodilla León (Eds.) Brill, pp.151-175. doi: 10.30965/9783846769133_008

- Grassin, A. S. 2022. Le tournant sensible de la médiation culturelle. *La Lettre de l'OCIM*, 10-17. doi: 10.4000/ocim.5040
- International Organization for Standardization. 2009. *Acoustics - Measurement of room acoustic parameters*. Part 1, *Performance spaces*. Excerpts from International Standard ISO3382-1.
- Katz, B. F. G. , C. Cros, S. Peichert, and J. De Muynke. 2024. The Past Has Ears at Notre-Dame: Acoustic digital twins for research and narration. *Digital Applications in Archaeology and Cultural Heritage*, SI: Digital Heritage Twins from Artificial Intelligence to Storytelling, vol. 34, pp. e00369:1–16, doi:10.1016/j.daach.2024.e00369.
- Katz, B. F. G., N. Eley, J. De Muynke, S. S. Mullins, and E. K. Canfield-Dafilou. 2024 (submitted). Experimental Virtual Archaeological-Acoustics: Studying Historical French Spaces and Performance Practice. In *Archaeoacoustics*, M. Kolar and K. Primeau (Eds.) Springer/ASA Press.
- Katz, B. F. G., D. Murphy, and A. Farina. 2020. The Past Has Ears (PHE): XR Explorations of acoustic spaces as Cultural Heritage. In *Proceedings of the Intl Conf on Augmented Reality, Virtual Reality and Computer Graphics (SALENTO AVR)*, vol. 12243, Lecture Notes in Computer Science, De Paolis, L. / Bourdot, P. (Eds.), pp.91-98.
- Katz, B. F. G., and E. A. Wetherill. 2005. Fogg art museum lecture room, a calibrated recreation of the birthplace of room acoustics. In *Proceedings of Forum Acusticum*, Budapest, 2191–2196.
- Kleiner, M., B.-I. Dalenbäck, and P. Svensson. 1993. Auralization - An overview. *Journal of the Audio Engineering Society* 41: 861–875.
- Kügler, K. 2019. The Manuscript Ivrea, Biblioteca Capitolare 115. *Introductory Study and Facsimile Edition*. Lucca: Libreria Musicale Italiana. ISBN 9788870969887.
- Labande, L. H. 1925. *Le Palais des Papes et les monuments d'Avignon au XIV^{ème} siècle*. Marseille: F. Detaille.

- Mainoldi, E. S. 2001. *Ars musica. La Concezione della musica nel medioevo*. Milan: Rugginenti.
- Morgan, M. 1914. *The Ten Books on Architecture. Vitruvius, Translated by Josephus Gwilt*; Harvard University Press: Cambridge, UK; Humphrey Milford: London, UK; Oxford University Press: Oxford, UK, 1–413.
- Mullins, S. S. 2024. *Des voix du passé : The historical acoustics of Notre-Dame de Paris and choral polyphony*. Ph.D. Thesis, Sorbonne Université, 2024.
<https://theses.hal.science/tel-04879114>.
- Mullins, S. S., and B. F. G. Katz. 2023. Immersive auralisation for choral ensembles. In *Proceedings of the International Conference on Auditorium Acoustics*, Institute of Acoustics, Athens, 1–9.
- Mullins, S. S., E. K. Canfield-Dafilou, and B.F.G. Katz. 2022. The development of the early acoustics of the chancel in Notre-Dame de Paris: 1160-1230. In *Proceedings of the Symposium on The Acoustics of Ancient Theatres*, Verona, 1–4.
- Mülleder, A., M. Romanov, N. Meyer-Kahlen, and F. Zotter. 2023. Do-it-yourself headphones and development platform for augmented reality audio. In *Proceedings of the Audio Engineering Society International Conference on Spatial and Immersive Audio*, Huddersfield, 30:1-8.
- Peichert, S., J. De Muynke, and B. F. G. Katz. 2024. Notre-Dame Whispers : a geolocated immersive walk through the sonic memory of Notre-Dame de Paris Cathedral, in *Proc. Gothic Resonances*, pp. 105–128, 2024, doi:10.5281/zenodo.14163355.
- Peichert, S., and J. De Muynke. 2023. Whispers of the Past at Notre-Dame: a geo-localised immersive walk through the sonic memory of Notre-Dame de Paris cathedral. At *Résonances Gothiques*, September 7–9, in Avignon, France.
- Poisson, J.-M. 2004. Le Palais des Papes d'Avignon: structures défensives et références symboliques. In *Les Palais dans la Ville*, dir. P. Boucheron, and J. Chiffolleau, 213-228. Lyon: Presses universitaires de Lyon.

- Postma, B. N. J., and B. F. G. Katz. 2015. Creation and method of virtual acoustic models for historic auralizations. In *Virtual Reality*, vol. 19: 161-180. Springer Nature. doi:10.1007/s10055-015-0275-3.
- Postma, B. N. J., and B. F. G. Katz. 2016. Perceptive and objective evaluation of calibrated room acoustic simulation auralizations. In *Journal of the Acoustical Society of America*, vol. 140, 4326–4337. doi:10.1121/1.4971422.
- Postma, B. N. J., A. Tallon, and B. F. G. Katz. 2015. Calibrated auralization simulation of the abbey of Saint-Germain-des-Prés for historical study. In *Proceedings of the International Conference on Auditorium Acoustics*, vol. 37, 190–197, Institute of Acoustics.
- Postma, B. N. J., E. Green, E. Kahle, and B. F. G. Katz. 2021. Pre-Sabine Room Acoustic Guidelines on Audience Rake, Stage Acoustics, and Dimension Ratios. In *Acoustics* 3, n° 2, 235-51. <https://doi.org/10.3390/acoustics3020017>.
- Schimmelpfennig, B. 1991. Aspekte des päpstlichen zeremoniells in Avignon. In *Aspects de la Musique Liturgique au Moyen Âge. Actes des Colloques de Royaumont de 1986, 1987 et 1988*, ed. M. Huglo, C. Meyer, and M. Peres, 229-243. Creaphis.
- Tanay, D. 1992. The Transition from the Ars Antiqua to the Ars Nova: Evolution or Revolution? In *Musica Disciplina, Vol. 46*, 79-104. American Institute of Musicology Verlag Corpusmusicae, GmbH.
- Tomasello, A. 1982. *Music and Ritual at Papal Avignon, 1309-1403*, UMI Research Press. ISBN 9780835714938.
- Vassilantonopoulos, S. L., and J. Mourjopoulos, J. 2003. A Study of Ancient Greek and Roman Theater Acoustics. *Acta Acustica United with Acustica*, vol. 89: 123–136.
- Vecchione, B. 2014. Une poétique du motet médiéval : Textes, hypotextes et niveaux de discours dans l'*Ave regina celorum*. In *Beyond 50 years of Ars Nova studies at Certaldo, 1959-2009: atti del convegno internazionale di studi, Certaldo, Palazzo Pretorio, 12-14 giugno 2009*, ed. M. Gozzi, A. Ziino, and F. Zimei, 69-133. LIM - Libreria Musicale Italiana. ISBN: 9788870967371.

Vingtain, D. 1998. *Avignon: le Palais des Papes*, Paris: Zodiaque.

Viollet-le-Duc, E. E. 1858. *Dictionnaire raisonné de l'architecture française du XIème au XVIème siècle*. Paris: B. Bance.